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Impact factors on rockfall movement using high-speed camera binocular stereo vision technology

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Abstract. Rockfall is a frequent and serious geological hazard in mountainous areas worldwide. It is of great significance to fully understand rockfall movement for disaster assessment and prevention. In this paper, based on the principle of binocular stereo vision, a filed experimental monitoring technology was developed to conduct the rockfall movement experiment research. Through the orthogonal experimental method, taking the block velocities obtained by binocular stereo vision system as a reference index, the impact factors such as the slope angles and the falling heights, shapes and masses of blocks on rockfall movement are studied. The lateral deviations and jumping heights of different blocks when they are released from the same falling height and moving along the same slope are presented. The results show that slope angle is the most key factor affecting block movement, while the falling heights, shapes and masses of blocks are the secondary factors. Moreover, the experimental methods and results of this paper can lay a foundation for the further study of rockfall movement characteristics.

Keywords. Rockfall movement, binocular stereo vision, field experiment, impact factor, orthogonal method.

1. Introduction

Rockfall is a common geological hazard in mountainous areas and always poses significant hazard to infrastructure, transportation lines and human activities [1]. In recent years, with the rapid development of water conservancy and hydropower, highway network, open-pit mines and other projects, the rockfall disasters caused by the collapse of dangerous rock masses on high and steep slopes have become more and more prominent [2]. Thus, research on rockfall hazards becomes increasingly urgent and important.

The rockfall movement is a key content in the study of rockfall hazards. At present, field investigation, mathematical calculation, model experiment, numerical simulation, and field experiment are the main methods to study rockfall movement. For example, Perret et al. [3] used 33 stem discs from previously felled Picea abies trees found at the foot of Schwarzenberg as samples, and a total number of 301 rockfall events were investigated to analyze the spatial and temporal rockfall activity in a subalpine forest stand. Azzoni et al. [4] established a mathematical model considering dynamic coefficients values, and rockfall trajectories on two different slopes were successfully predicted. Li et al. [5] performed a series of lab experiments of rockfall movement using an apparatus specifically built, and the coefficient of restitution and kinetic energy loss rate of rockfall impacts were studied. Chen et al. [6] compared the movement characteristics (such as kinetic energy, trajectory, and bounce height) of rockfall obtained by two-dimensional and three-dimensional DDA, and pointed out the advantages of 3D numerical simulation. Huang et al. [7] carried out field experiments in Lugu Iron Mine, Mianning County, Sichuan Province, and analyzed the effects of block masses, block shapes and slope conditions on rockfall movement characteristics. It can be found from the above researches that these methods have made great contributions to the study of rockfall movement. However, field investigation is often limited by the subjective role of researchers [8]. Mathematical calculation generally adopts many simplified conditions in the process of theoretical derivation, which makes the analysis results tend to be conservative [9]. The results of model experiment are greatly affected by the scale effect of the materials and geometry of the slopes and blocks [5]. Numerical simulation depends on the setting of numerical parameters, and the reliability of the results needs to be verified by actual engineering and field experiments [10]. By comparison, field experiment can analyze the rockfall movement in real situation, and the obtained results tend to have high credibility and strong persuasiveness [11].

Therefore, in this study, a series of field experiments of rockfall movement are carried out by the developed high-speed camera binocular stereo vision technology. The high-speed camera binocular stereo vision system and automatic release apparatus for rockfall movement are introduced. Taking the block velocities as a reference index, the impact factors such as the slope angles and the falling heights, shapes and masses of blocks on rockfall movement are studied by the orthogonal experiment method. The influence degrees of the factors on rockfall movement are compared, and the primary and secondary impact factors are pointed out.

2. Experimental apparatuses

2.1. High-speed camera binocular stereo vision system

The high-speed camera binocular stereo vision system is based on the principle of three-dimensional coordinate [12]. That is, this system uses two high-speed cameras in different positions to image the same object, and recovers the coordinate information of the object to be measured from the disparity. Two sets of AcutEye long-term high-speed shooting systems are used to form a binocular camera stereo vision system. Each shooting system mainly consists of Optronis high-speed cameras, CoaXPress high-speed image acquisition cards, Acute image data processing software, dedicated synchronization controller and PC storage systems, as shown in Figure 1. The high-speed cameras have an operating speed of 250 fps and a resolution of 640 × 480 pixel. An AcuteSync-20K synchronization controller is used to make high-precision synchronous shooting of two cameras.

In the experiment, each face of the blocks was labelled with coded marks. Two synchronous high-speed cameras can capture the spatial movement of coded marks on blocks, and the accelerations of the corresponding blocks can be directly extracted and output by the acute image data processing software. Through the obtained accelerations, the movement parameters such as velocities and displacements of blocks can be further calculated. At the same time, the movement states at every moment can also be recorded by the high-speed shooting systems. This information is the important research content of rockfall movement.

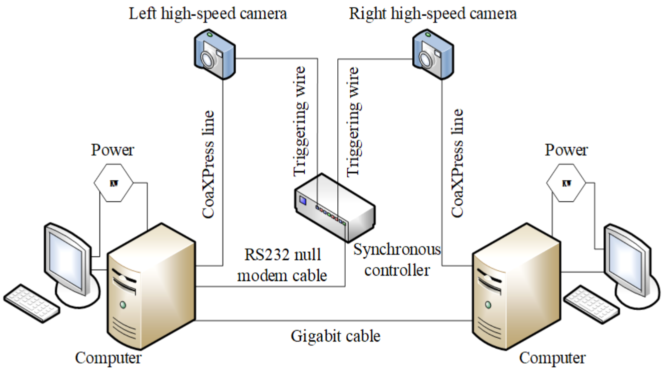


Figure 1. High-speed camera binocular stereo vision system

Figure 2. Automatic release apparatus for rockfall

2.2. Automatic release apparatus

To control the instantaneous start of falling blocks under different conditions, an automatic release apparatus was developed for rockfalls, as shown in Figure 2. The main components included the electric crane and steel frame for holding blocks. To lift steel frame for holding blocks to the appropriate height and fix the electric crane, a trapezoidal steel frame is welded as a fixed base for the crane, and the steel pipes are used to constrain the base to prevent the release apparatus from overturning. During the experiment, the blocks that need to be studied are placed in steel frame for holding blocks. Then, the crane is used to lift the steel frame for holding blocks to the required height. When the binocular stereo vision system at the bottom of the slope is ready, the power of the magnetic lock of the steel frame for holding blocks can be disconnected, the bottom plate of the steel frame for holding blocks can be opened instantaneously, and the blocks can be released by freefalling.

3. Experimental program

3.1. Experimental slopes and blocks

The experimental slopes (Figure 3) are located near an abandoned section of the G318 national highway in Mozhugongka County, Lhasa city, Tibet Autonomous Region, China. Three slopes are selected, with average slope angles of 52°, 34° and 24°, and slope lengths of 10.0 m, 14.0 m and 19.5 m, respectively. The selected slopes have sparse vegetation and bare rocks, which are suitable for block movement. Granite blocks are selected as experimental blocks with a density of 2680 kg/m^3. The blocks have three shapes, i.e., cube, cuboid and regular octahedron (Figure 4). The corresponding block numbers, dimensions and masses are listed in Table 1.

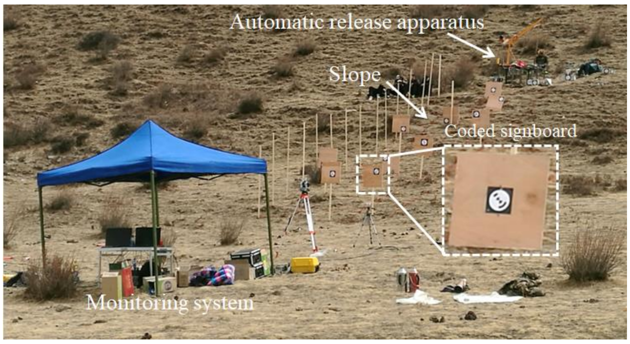


Figure 3. Experimental slope with the slope angle of 34°.

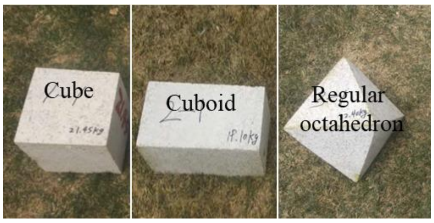


Figure 4. Experimental blocks of different shapes.

3.2. Orthogonal experiment

Rockfall movement is a complex dynamic process affected by many factors. Scholars believe that the representative impact factors may be the slope angles and the falling heights, shapes and masses of blocks [7, 13]. In this section, the influences of these factors on rockfall movement are studied. The orthogonal experiment method is adopted, and three levels are selected for each impact factor. The orthogonal design is listed in Table 2, and each group of experiments is performed six times to obtain more reliable results.

Table 1. Description of experimental blocks

Shape	Number	Mass (kg)	Dimension (m)
	1-1	21.25	Edge length 0.20
Cube	1-2	41.20	Edge length 0.25
	1-3	70.60	Edge length 0.30
	2-1	19.10	0.36 × 0.15 × 0.15
Cuboid	2-2	42.45	0.40 × 0.20 × 0.20
	2-3	63.65	0.52 × 0.22 × 0.20
	3-1	22.40	Edge length 0.26
Regular octahedron	3-2	40.65	Edge length 0.32
	3-3	68.40	Edge length 0.38

Table 2. Orthogonal experimental design

Group	*A* Slope angle (°)	*B* Falling height (m)	*C* Block shape	*D* Block mass (kg)
1	24	0.5	Cube	21.45
2	24	1.0	Cuboid	42.45
3	24	1.5	Regular octahedron	68.40
4	34	0.5	Cuboid	63.45
5	34	1.0	Regular octahedron	22.40
6	34	1.5	Cube	41.20
7	52	0.5	Regular octahedron	40.65
8	52	1.0	Cube	70.60
9	52	1.5	Cuboid	19.10

4. Results and discussion

Taking the block velocities obtained by binocular stereo vision system as a reference index, the impact factors on block movement are analyzed. The experimental results are listed in Table 3. K_{ij} is the sum of the average velocities corresponding to the level of factor j in column i, and k_{ij} is the average value of K_{ij}. Here, $i = A$, B, C, and D, and $j = 1$, 2, and 3. R is the difference between the maximum and minimum average velocities of the factors in column i, which is called the extreme difference of the average velocities of blocks. The detailed description on the calculation of K_{ij}, k_{ij}, and R can also be found in Huang et al. [7]. The greater the extreme difference in the average velocities of block movement, the greater the impact of the corresponding factors on block movement. On the contrary, the smaller the extreme difference, the smaller the impact of the corresponding factors on block movement. The extreme difference R_A is much greater than the extreme difference R_B, R_C, and R_D. That is, the influence degree of these factors on block movement is compared as follows: A (slope angle) > D (block mass) > B (falling height) > C (block shape). Therefore, slope angle is the most key factor affecting block movement, while the extreme differences of the other three factors is relatively small and similar, which can be regarded as secondary factors.

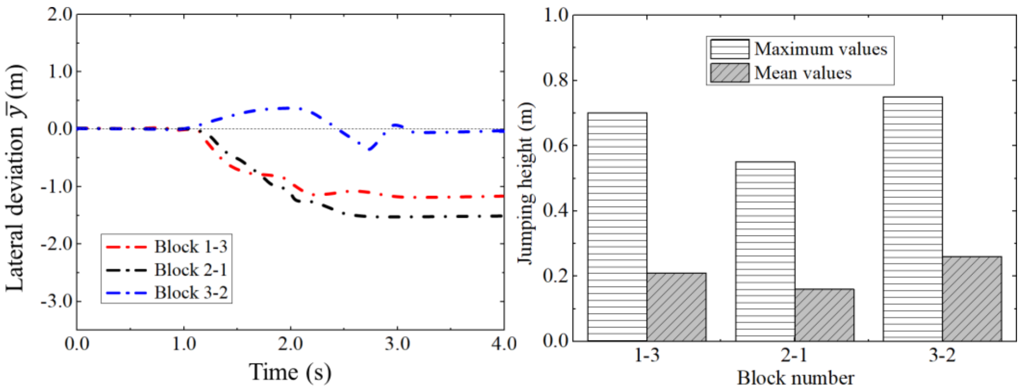
It can be seen from Table 3 that $k_{A3} > k_{A2} > k_{A1}$, and thus A_3 is the high level of factor A. That is, when the slope angle is A_3 (52°), the average velocity of block movement is the highest. Similarly, B_3 is the high level of factor B, and the average block velocity is the highest when the falling height is B_3 (1.5 m). C_3 is the high level of factor C, and the average block velocity is the highest when the block shape is C_3 (octahedron). D_2 is the high level of factor D, and the average block velocity is the highest when the block mass is D_2 (42.45 kg). It can be seen that when the factors are combined in the form of $A_3B_3C_3D_2$, the average velocity of block movement may be the largest. The rockfall experiment with combination factors of $A_3B_3C_3D_2$ is also performed, and six sets of the experiment are conducted to obtain the average velocity of block movement. The average block velocity is 3.71 m/s, which is significantly larger than the maximum value of the average block velocities of the nine groups of rockfall experiments in the experimental scheme in Table 2. This proves that the experimental results are correct for the analysis of the extreme difference of block velocity.

To further demonstrate the movement characteristics of rockfall, Figure 5 gives the history curves of lateral deviations and jumping heights of blocks 1-3, 2-1, and 3-2 when the blocks are released from falling height of 1.0 m and moving along the 52° slope. As shown in Figure 5(a), the average lateral deviations $\overline{y}$ of the blocks are compared as follows in numerical values: cuboid > cube > regular octahedron, where the $\overline{y}$ of the cube and cuboid is negative, and the $\overline{y}$ of the regular octahedron changes left and right around the slope centreline. When the regular octahedron becomes stationary, it has a negative value close to the slope centreline, with a small lateral deviation. As shown in Figure 5(b), the maximum and average jumping heights of the different shapes of the blocks are compared as cuboid <

cube < regular octahedron, i.e., opposite of the effect of the block shape on the block lateral deviation. The closer the block shape is to a sphere, the smaller the block moves sideways, and the greater the jumping height.

Table 3. Experimental results

Group	*A* Slope angle (°)	*B* Falling height (m)	*C* Block shape	*D* Block mass (kg)	Y_k average velocity (m/s)
I	1(24)	1(0.5)	1(Cube)	1(21.45)	0.84
II	1(24)	2(1.0)	2(Cuboid)	2(42.45)	0.96
III	1(24)	3(1.5)	3(Regular octahedron)	3(68.40)	1.21
IV	2(34)	1(0.5)	2(Cuboid)	3(63.65)	1.23
V	2(34)	2(1.0)	3(Regular octahedron)	1(22.40)	1.77
VI	2(34)	3(1.5)	1(Cube)	2(41.20)	2.51
VII	3(52)	1(0.5)	3(Regular octahedron)	2(40.65)	3.68
VIII	3(52)	2(1.0)	1(Cube)	3(70.60)	3.22
IX	3(52)	3(1.5)	2(Cuboid)	1(19.10)	3.39
K_{i1}	3.0100	5.7500	6.5700	6.0000	
K_{i2}	5.5100	5.9500	5.5800	7.1500	$\sum_{k=1}^{9} Y_k = 18.81$
K_{i3}	10.2900	7.1100	6.6600	5.6600	
k_{i1}	1.0033	1.9167	2.1900	2.0000	
k_{i2}	1.8367	1.9833	1.8600	2.3833	$\overline{Y} = 2.09$
k_{i3}	3.4300	2.3700	2.2200	1.8867	
R	2.4267	0.4533	0.3600	0.4967	$\overline{R} = 0.93$



(a) (b)

Figure 5. Movement parameters. (a) Lateral deviation-time curves. (b) Jumping heights.

5. Conclusions

In this paper, a filed experimental monitoring technology is developed based on the principle of binocular stereo vision, and a series of rockfall movement experiments are carried out. Considering the impact factors such as the slope angles and the falling heights, shapes and masses of blocks, the orthogonal experimental design method is adopted to study rockfall movement using the block velocities as a research index. The influence degree of the factors on block movement is follows: slope angle > block mass > falling height > block shape. Slope angle is the most important impact factor on block movement, and the falling heights, shapes and masses of blocks are the secondary factors. When the impact factors are combined in the form of $A_3B_3C_3D_2$, the average movement velocity of the block is the largest. The average lateral deviations of the blocks are compared in numerical values: cuboid > cube > regular octahedron. The regular octahedron has a small lateral deviation when it becomes stationary. However, the maximum and average jumping heights of the different shapes of the blocks are compared as cuboid < cube < regular octahedron. If the block shape is close to a sphere, the block deviations would become small, while the jumping height would become obvious. The results of this paper can lay a foundation for the study of rockfall movement characteristics, and more studies and interesting conclusions will be presented using the developed high-speed camera binocular stereo vision technology.

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References

[1] Asteriou, P., Saroglou, H., Tsiambaos, G., Geotechnical and kinematic parameters affecting the coefficients of restitution for rock fall analysis. International Journal of Rock Mechanics and Mining Sciences, 2012. 54: 103-113.

[2] Yan, P., Zhang, J.H., Kong, X.Z., Fang Q., Numerical simulation of rockfall trajectory with consideration of arbitrary shapes of falling rocks and terrain. Computers and Geotechnics, 2020. 122: 103511.

[3] Perret, S., Stoffel, M., Kienholz, H., Spatial and temporal rockfall activity in a forest stand in the Swiss Prealps-A dendrogeomorphological case study. Geomorphology, 2006. 74(1-4): 219-231.

[4] Azzoni, A., Barbera, G.L., Zaninetti, A., Analysis and prediction of rockfalls using a mathematical model. International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts, 1995. 32(7): 709-724.

[5] Li, L.P., Sun, S.Q., Li, S.C., Zhang, Q.Q., Hu, C., Shi, S.S., Coefficient of restitution and kinetic energy loss of rockfall impacts. KSCE Journal of Civil Engineering, 2016. 20(6): 2297-2307.

[6] Chen, G.Q., Zheng, L., Zhang, Y.B., Wu, J., Numerical simulation in rockfall analysis: A close comparison of 2-D and 3-D DDA. Rock Mechanics and Rock Engineering, 2013. 46: 527-541.

[7] Huang, R.Q., Liu, W.H., Zhou, J.P., Pei, X.J., Rolling tests on movement characteristics of rock blocks. Chinese Journal of Geotechnical Engineering, 2007. 29(9): 1296-1302.

[8] Bettina, K., Hannah, T., Rudolf, S., Gertraud, M., Johann, S., High Mountain rockfall dynamics: rockfall activity and runout assessment under the aspect of a changing cryosphere. Geografiska Annaler: Series A, Physical Geography, 2021. 103(1): 83-102.

[9] Irfan, M., Chen, Y., Segmented loop algorithm of theoretical calculation of trajectory of rockfall. Geotechnical and Geological Engineering, 2017. 35(1): 377-384.

[10] Ma, K., Liu, G.Y., Three-dimensional discontinuous deformation analysis of failure mechanisms and movement characteristics of slope rockfalls. Rock Mechanics and Rock Engineering, 2022. 55(1): 275-296.

[11] Lambert, S., Bourrier, F., Gotteland, P., Nicot, F., An experimental investigation of the response of slender protective structures to rockfall impacts. Canadian Geotechnical Journal, 2020. 57(8): 1215-1231.

[12] Zhao, P.H., Li, J.J., Kang F., Slope surface displacement monitoring based on a photogrammetric system. Optik-International Journal for Light and Electron Optics, 2021. 227:166089.

[13] Liu, G.Y., Li, J.J., A three-dimensional discontinuous deformation analysis method for investigating the effect of slope geometrical characteristics on rockfall behaviors. International Journal of Computational Methods, 2019. 16(8): 1850122.